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Aggregation and Control of Flexible Consumers – A Real Life Demonstration

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Abstract: In this paper, we present an architecture for aggregation and control of a portfolio of flexible consumers. The architecture makes it possible to control the aggregated consumption of the portfolio to follow a power reference while honoring local consumer constraints. Hereby, an aggregator is able to utilize a portfolio of consumers as a virtual power plant to deliver services in the electricity markets. The architecture is implemented and demonstrated in a field test on a portfolio consisting of 54 heat pumps each located in an inhabited household. In this demonstration, a power reference varying between 15 kW and 35 kW is followed over a 7 day period. The field test showed satisfactory performance in terms of following the power reference and assuring comfort for the inhabitants. To the best knowledge of the authors, this is the first real life demonstration where a power reference is followed based on the aggregated consumption of a larger number of devices – and consequently a significant step towards the smart grid vision.

Keywords: Smart grid, demand response, flexible consumers, electrical grid, field test.

1. INTRODUCTION

Many actions have been taken from a political point of view to increase the penetration of renewables throughout the world. A few examples are renewable portfolio standards or goals that ensure a certain percentage of renewables in almost all states in the US and a European Union energy target of 20 % energy consumption from renewables by 2020.

As the renewable penetration increases, the conventional generators are phased out. This, however, causes a major challenge: the central power plants do not only deliver electricity but also provide stabilizing ancillary services to ensure a reliable and secure electrical power system. The ability to provide such services in the classical sense disappears as the conventional power plants are replaced by renewable energy resources. The reason is that keeping renewables in reserve will entail that free energy is wasted making this a very expensive solution. Further, many renewable sources are characterized by highly fluctuating electricity generation and can suddenly increase or decrease production depending on weather conditions, making it difficult to deliver such services.

It is therefore evident that alternative sources of stabilizing services must be established as renewables replace conventional generation. One of the approaches to obtain such services is the *smart grid* concept, where demand-side devices with flexible power consumption take part in the balancing effort. The basic idea is to let an aggregator control a portfolio of flexible devices such as heating and cooling devices. Hereby, the aggregator can act as a *virtual power plant* and utilize the accumulated flexibility in the electricity markets on equal terms with conventional generators (Energinet.dk and Danish Energy Association (2012); Petersen et al. (2013)).

A most important aspect in enabling an aggregator to participate in the electricity markets is the ability to control a number of devices such that the sum of the devices' consumption follows a power reference. Therefore it is also the topic of many recent works. A few examples are: aggregation and control of thermostatic loads (Kalsi et al. (2011)), control of heating systems such as heat pumps (Masuta et al. (2011); Schafer et al. (2012), refrigeration systems (Rahnama et al. (2013); **?**), etc. However, while these works describe a virtual power plant setup where demand side devices are used to deliver system-stabilizing services, they are all purely based on simulations and no field demonstration.

Demonstrations showing the concept of demand response do exist. The Dutch PowerMatching concept is an agent based method for demand response which was demon-

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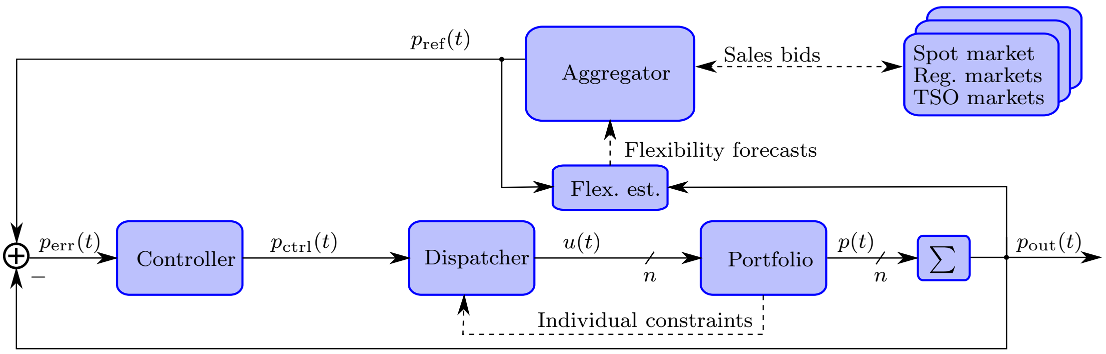

Fig. 1. Overall system architecture. Solid arrows indicate signals while dashed arrows indicate information exchange.

strated on 25 households (Bliek et al. (2010)). Another example is the Danish EcoGrid EU demonstration, where demand response from a large number of customers was obtained via price mechanisms (Jørgensen et al. (2011)). A third example is the Olympic Peninsula Project (Hammerstrom (2007)) where the ability to affect consumer behavior through real time prices was demonstrated. Common for these demonstrations is the use of price mechanisms causing a demand response. If implemented with an outer control loop, such price incentive mechanisms could be used to control consumers to follow a power reference; however, this is not done any of the above demonstrations.

Other examples of demonstrations within the smart grid field focus on control of individual consumers. In Pedersen et al. (2011), a direct control method was used on heat pumps to perform optimization towards the electricity spot prices. The focus of Douglass et al. (2011) was a demonstration of how refrigeration systems can respond to local grid measurements and thereby provide a system-stabilizing service. In Pedersen et al. (2013), a controller for a single refrigeration system was developed and it was demonstrated that is was possible to store and release energy. The class of demonstrations of control of individual devices is large – but does not show how a portfolio of devices can deliver a desired *aggregated* response.

To the best knowledge of the authors of this paper, no demonstration has been made where a power reference is followed by the aggregated consumption of a portfolio of flexible consumers. In this work, such a demonstration is completed: The consumption of 54 heat pumps located in different households is controlled to follow a power reference over a 7-day period while local consumer comfort constraints are honored.

First, in Sec. 2, an architecture for aggregation and control of a large portfolio of flexible consumers is presented. Following in Sec. 3, the architecture is applied to a real life portfolio of 54 households equipped with heat pumps, and finally in Sec. 4 and Sec. 5 we show the demonstration results and conclude the work.

2. SYSTEM ARCHITECTURE

This section describes an architecture for aggregation and control of flexible consumers. The overall criteria for the system architecture are as follows:

(1) Enable the portfolio to follow a power reference.
(2) Handle a large number of devices (up to thousands).
(3) Be simple and transparent.
(4) Ensure that local consumer constraints are honored.

The ability to follow a power reference will enable the consumer portfolio to deliver most electricity services (if implemented with the right sampling time) which is an important element in the smart grid vision. The ability to be able to manage many devices is likewise a most important smart grid aspect. The simplicity constraint is chosen to allow a setup simple enough to implement and demonstrate in a field test. Finally, the bullet assuring that local constraints are honored is vital, as the consumers in the portfolio are mainly concerned about their local primary process – and not about their ability to deliver electricity services.

The system architecture illustrated in Fig. 1 satisfies these criteria. In the following, the architecture is presented at an overall level and next, in Sec. 3, the architecture is applied to a real life setup.

2.1 Components in the system architecture

Portfolio The portfolio is a collection of n flexible consumers [1] that can be remotely controlled within certain user-defined constraints. The control inputs are denoted $u(k) \in \mathbf{R}^n$, the power consumption of the devices are denoted $p(k) \in \mathbf{R}^n$, and the aggregated consumption is denoted $p_{\mathrm{out}}(k) \in \mathbf{R}$ and given by $p_{\mathrm{out}}(k) = \sum_{i=1}^{n} p_i(k)$ where k is the sample number.

Flexibility Estimator The flexibility estimator forecasts the consumption flexibility of the portfolio and makes this information available for the aggregator as indicated by the dashed arrow in Fig. 1. This allows the aggregator to get an overview of the available flexibility and act accordingly in the markets. The flexibility can be estimated in various ways, for example by examining the power reference $p_{\mathrm{ref}}(k)$ and the actual consumption $p_{\mathrm{out}}(k)$ over time. Other relevant parameters such as weather forecasts can also be used by the flexibility estimator to make a more accurate estimate of the consumer flexibility.

Aggregator The aggregator is an entity that has entered into contracts with owners of the flexible devices allowing the aggregator to actively utilize the aggregated consumer flexibility. This ability can be used to participate in the

[1] For simplicity, we use the term *consumer* to denote a *flexible consumption device* throughout the work.

electricity markets, as indicated in Fig. 1. By using the knowledge from the flexibility estimator, the aggregator can optimize the available flexibility towards the different markets and actuate the portfolio accordingly via the portfolio consumption reference $p_{\mathrm{ref}}(k) \in \mathbf{R}$.

Controller The input to the controller is the tracing error $p_{\mathrm{err}}(k) = p_{\mathrm{ref}}(k) - p_{\mathrm{out}}(k)$ and the output is a control signal $p_{\mathrm{ctrl}}(k) \in \mathbf{R}$ which is fed to the dispatcher according to a given feedback control law.

Dispatcher The dispatcher distributes the scalar control signal $p_{\mathrm{ctrl}}(k)$ to the n devices in the portfolio via the control vector $u(k)$. In doing this, the dispatcher takes the local constraints of the individual devices into consideration as indicated by the dashed arrow from portfolio to dispatcher in Fig. 1. The dispatch strategy can for example be based on simple sorting algorithms, which makes the dispatcher very fast even for portfolios comprised of thousands of devices (Biegel et al. (2013)).

3. REAL LIFE DEMONSTRATION

A portfolio consisting of real life inhabited households heated with heat pumps is used to demonstrate the proposed system architecture. In the following, we first describe the actual demonstration setup and what the limitations are, and following how the control architecture presented in Sec. 2 is implemented. The actual demonstration results are presented in Sec. 4.

3.1 Portfolio of households heated with heat pumps

The platform *Styr din varmepumpe* (meaning: Control your heat pump) consisting of 300 households with heat pump heating is used to demonstrate the presented architecture. This platform is briefly described in the following.

Overall setup The houses are all real life inhabited houses in different locations in Denmark. The houses vary from smaller houses with a total area of 100 m^2 to larger houses with an area of 400 m^2. Further, the houses vary in type: some are old houses built in the 1850s while other houses are newly built.

Also the heat pumps are different; more than 50 different heat pump designs are present in the platform with some pumps being water-to-water while others are air-to-water based. Moreover, the heating systems vary much in the individual houses: all the houses have a heat pump but some of the houses use underfloor heating while other have radiators. Additionally, some of the houses are equipped with other heating sources than the heat pump, for example a wood stove or solar heating. *Consequently, we are dealing with a realistic real life heterogeneous household portfolio representative of typical Danish households.*

Sensors and actuator The households included in this platform have all installed the heat pumps before being a part of the platform. The communication- and sensor equipment has therefore been subsequently installed as shown in Fig. 2. These sensors include a power measurement of the heat pump, a single indoor thermometer, and various flow meters.

Fig. 2. One of the 54 domestic heat pumps subsequently installed with sensors and actuator that can be accessed over an Internet connection.

The heat pumps are equipped with a relay that can be switched between ON and OFF. In the ON-mode, the heat pump will act according to the local embedded control strategy that assures the desired indoor temperature, sufficient hot water, etc. In other words: the ON-mode allows the heat pump to operate, but it *does not* force the heat pump to start. On the contrary, the OFF-mode *will* force the heat pump to shut down.

The sensor data and the ON/OFF control commands are transmitted over an Internet connection to a server via a Linux-in-a-Box system (the box seen in the top on Fig. 2). The sampling time of the communication link between heat pump and the server is 5 minutes.

Setup limitations A number of system restrictions limit the abilities to apply the presented control architecture. First, only 54 of the houses are suitable to be remotely controlled due to various issues on the remaining heat pumps. The demonstration therefore relies on aggregation and control of these 54 households. Another very limiting factor is a non-deterministic communication delay in the order of $5 - 10$ minutes and on some occasions of up to 25 minutes [2]. For this reason, a power reference with a resolution of one hour is chosen (which could alternatively be denoted an energy per hour reference).

3.2 Implementation of proposed architecture

In the following, the implementation of the blocks in Fig. 1 on the heat pump platform is described. Notice that a 5 minute sampling time is used in the control; however, the power reference $p_{\mathrm{ref}}(k)$ is kept constant within each hour due to the slow communication link.

[2] The devices and the server *pulls* data with a sampling time of 5 minutes causing an expected delay up to 10 minutes and even higher if transmission errors occur.

Portfolio The control signal to the $n = 54$ heat pumps is $u(k) \in \{0,1\}^n$, where $u_i(k) = 1$ corresponds to ON while $u_i(k) = 0$ corresponds to OFF for pump i. The power consumption of the individual houses is measured and communicated such that $p_{\text{out}}(k)$ is available to the controller as illustrated in Fig. 1.

The heat pumps have a number of local constraints that must be honored. These are:

(1) Runtime and stoptime constraints. To protect the heat pump equipment, the pump must remain ON for at least 30 minutes when switched from OFF to ON. Similarly when turned OFF.
(2) Temperature constraints. The indoor temperature in the houses must be kept within certain user-defined temperature bounds.
(3) Hot water constraint. There must always be hot water available in the hot water tank.

These constraints must be honored to ensure customer satisfaction. As illustrated in Fig. 1, the devices are able to communicate these individual constraints to the dispatcher which is responsible that they are honored.

Dispatcher The dispatcher must distribute the control signal $p_{\text{ctrl}}(k)$ among the n heat pumps without violating the three local constraints described above. This is done by implementing a method close to the one presented in Biegel et al. (2013) as described in the following.

First, the dispatcher examines if more than 30 L of hot water has been used during an OFF period for any heat pump that is still OFF. If this is the case, the aggregator registers that these pumps should be turned ON such that water can be heated. Let $n_{\text{hw}}(k) \in \mathbf{Z}_+$ denote the number of pumps that must be turned ON for this reason.

Following, the dispatcher determines the number of heat pumps $n_{\text{sw}}(k) \in \mathbf{Z}$ that should be switched from OFF to ON (or vice versa if $n_{\text{sw}}(k)$ is negative) such that the expected heat pump consumption equals the control signal $p_{\text{ctrl}}(k)$ at time sample k. By assuming that each heat pump has a constant power consumption given by $\overline{p} \in \mathbf{R}$, the number $n_{\text{sw}}(k)$ can be determined as

$$n_{\text{sw}}(k) = \text{round}\left(p_{\text{ctrl}}(k)/\overline{p} - \mathbf{1}^T u(k-1) - n_{\text{hw}}(k)\right) \quad (1)$$

where $u(k-1) \in \mathbf{R}^n$ is the ON/OFF-state at the previous sample and round$(\cdot)$ is the "round to nearest integer" function.

The temperature and runtime constraints are honored as described in the following. Let the set $\mathcal{I} = \{1,\dots,n\}$ represent the entire heat pump portfolio and let the subset $\mathcal{I}_{\text{up}}(k) \subseteq \mathcal{I}$ denote the heat pumps that are able to provide upward regulation [3] by being able to be switched from ON to OFF at time sample k; similarly, let $\mathcal{I}_{\text{dn}}(k) \subseteq \mathcal{I}$ denote the heat pumps that are able to be switched from OFF to ON. The dispatcher forms the set $\mathcal{I}_{\text{up}}(k)$ by identifying the heat pumps that currently are ON and have been ON longer time than the stoptime constraint. The set $\mathcal{I}_{\text{dn}}(k)$ is determined in a similar manner.

The temperature constraints are incorporated by looking at the temperature of each single device relative to the temperature bounds set by the device owner. Let $T_{\min}, T_{\max} \in \mathbf{R}^n$ denote the indoor temperature bounds specified by the individual heat pump owners and let $T(k) \in \mathbf{R}^n$ be the temperatures measured at time sample k across the portfolio. Finally, let $s(k) \in \mathbf{R}^n$ be the *state of charge* of the devices defined as

$$s_i(k) = (T_i(k) - T_{\min,i})/(T_{\max,i} - T_{\min,i}). \quad (2)$$

If $n_{\text{sw}} > 0$, which means that devices must be switched from OFF to ON, the dispatcher will choose the devices with the lowest state of charge and vice versa if $n_{\text{sw}} < 0$. The following pseudo code describes this algorithm.

Initialize $u(k) := u(k-1)$;
Assign $u_i(k) := 1$ for the $n_{\text{hw}}(k)$ devices that have consumed 30 L hot water or more while pump is OFF;
Collect control signal $p_{\text{ctrl}}(k)$ and find $n_{\text{sw}}(k)$ by (1);
for $j = 1,\dots,|n_{\text{sw}}(k)|$ **do**
  Update $\mathcal{I}_{\text{up}}(k), \mathcal{I}_{\text{dn}}(k)$;
  if $n_{\text{sw}}(k) > 0$ **and** $\mathcal{I}_{\text{dn}} \neq \emptyset$ **then**
    Find the least agile device that can provide downward regulation: $i := \text{argmin}_{i\in\mathcal{I}_{\text{dn}}} s_i$;
    Switch device ON: $u_i(k) := 1$;
  else if $n_{\text{sw}}(k) < 0$ **and** $\mathcal{I}_{\text{up}} \neq \emptyset$ **then**
    Find the least agile device that can provide upward regulation: $i := \text{argmax}_{i\in\mathcal{I}_{\text{up}}} s_i$;
    Switch device OFF: $u_i(k) := 0$;
  end
end
Apply $u(k)$ to the portfolio;

Controller The power consumption patterns of the individual heat pumps are not identical and will also vary over time depending on local circumstances as illustrated later in Fig. 4 subplot (a). The role of the controller is to apply feedback control to the entire portfolio, such that the local disturbances are canceled out and the overall reference $p_{\text{ref}}(k)$ is followed.

In this work we construct a controller that seeks to follow a 1-hour power reference (or energy/hour reference). Such a controller is desired for example if the aggregator trades in hourly electricity markets. The reason for this choice is the practical limitations in the setup: the sampling time of 5 minutes and in particular the non-deterministic delay up to 25 minutes makes it impossible to follow a power reference with higher resolution.

The controller is implemented as a discrete PI-controller where the integral term is reset at the start of each hour. The controller operates with a sampling time of 5 minutes according to the following law:

$$p_{\text{err}}(k) = p_{\text{ref}}(k) - p_{\text{out}}(k) \quad (3)$$

$$p_{\text{err,I}}(k) = \begin{cases} p_{\text{err,I}}(k-1) + p_{\text{err}}(k) & \text{if } \text{mod}(k,12) \neq 1 \\ p_{\text{err}}(k) & \text{if } \text{mod}(k,12) = 1 \end{cases} \quad (4)$$

$$p_{\text{ctrl}}(k) = p_{\text{ref}}(k) + K_{\text{P}} p_{\text{err}}(k) + K_{\text{I}} p_{\text{err,I}}(k) \quad (5)$$

where $K_{\text{P}}, K_{\text{I}} \in \mathbf{R}$ are the controller gains. The modulus function mod$(\cdot)$ assures that the integrated error is reset every time a new hour has begun, i.e. every 12th sample. Hereby the controller will compensate for a reference tracing error inside each hour – but an error in one hour will not affect the following hour.

[3] Notice that production terms are used such that upward regulation corresponds to increased production or reduced consumption.

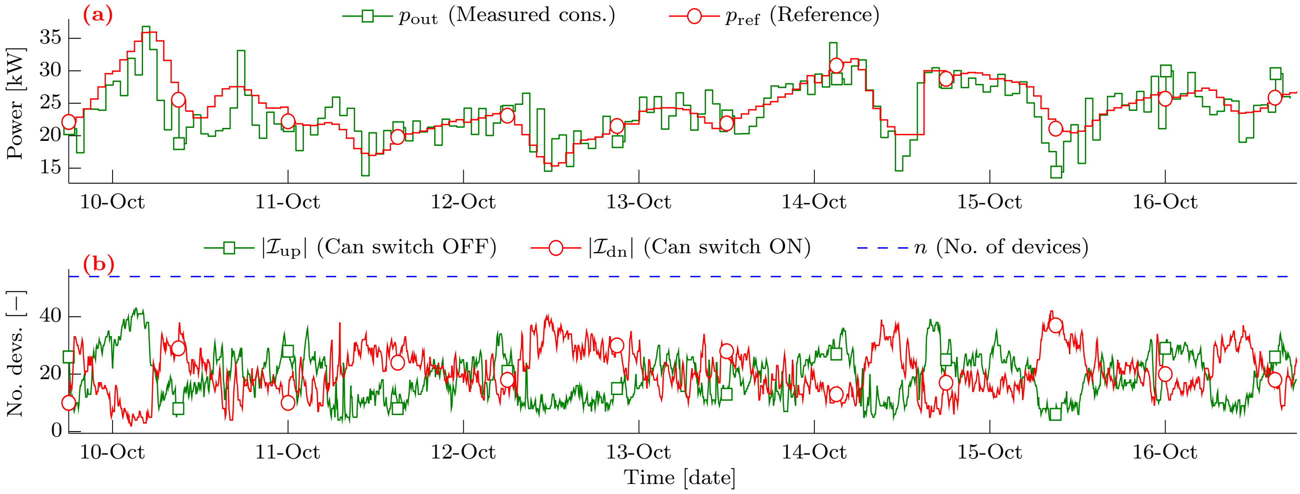

Fig. 3. Experimental results. Subplot (a): Tracing ability. Subplot (b): Device available to be turned ON/OFF.

3.3 Scope and limitations

As the goal of this work is to show that it is possible to follow a power reference based on a larger portfolio of flexible devices, the main focus has been put on the dispatcher and controller. The implementation of a flexibility estimator and aggregator is outside the scope of this work. Ideally, the portfolio flexibility would be estimated and optimized towards electricity spot price predictions and possibly regulating power prices to generate a power reference $p_{\text{ref}}(k)$. Instead, we simply construct a varying power reference every day at midnight for the 24 hours of the following day and just assure that the amplitude of the reference is sufficiently low such that it can be followed with satisfactory performance.

4. RESULTS

The setup described in the previous section has been implemented on 54 individual inhabited households and tested in a real life demonstration from 9th to 16th of October 2013. In the following, the demonstration results are presented.

4.1 Overall reference following ability

An hourly power reference is generated each day at midnight for the 24 hours of the following day. Due to the limitations in the setup, the power reference is kept close to the expected consumption of the portfolio.

In Fig. 3 subplot (a), the reference is shown and compared with the measured aggregated consumption of the heat pump portfolio. Subplot (a) shows that the portfolio indeed is able to follow the reference with a reasonable performance. The reason for the deviation between reference and measured output is a combination of two things. First, it is because of the very fluctuating power consumption of the individual heat pumps, and second, it is because the controller is implemented with very small control gain due to the large non-deterministic communication delay in the system, as previously described.

Subplot (b) shows the cardinality of $\mathcal{I}_{\text{up}}$ and $\mathcal{I}_{\text{dn}}$, i.e. it shows how many devices are able to provide upward and downward regulation, respectively, and compares this to the total number of devices which is $n = 54$. We notice that throughout the whole week, there are always some devices available for both upward and downward regulation, respectively, i.e. $\mathcal{I}_{\text{up}}(k), \mathcal{I}_{\text{dn}}(k) \neq \emptyset$ during the whole test. However, the slow PI controller is not able to exploit these available devices to follow the reference more accurately because of the low controller gain. As described previously, the gain is chosen this low due to the long non-deterministic communication delays in the setup.

4.2 Closeup on one heat pump

To further examine the setup, we observe the operation of one of the 54 heat pumps in the portfolio during the first 48 hours of the demonstration, see Fig. 4.

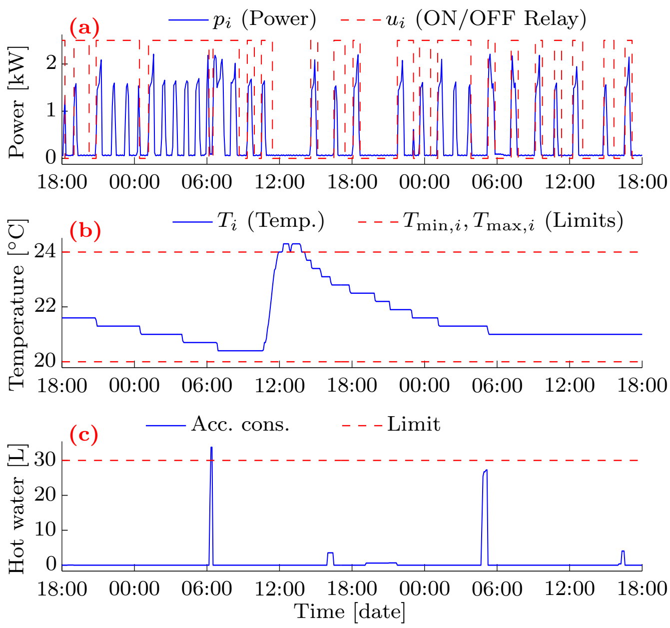

Fig. 4. Measurements from a single heat pump. Subplot (a): ON/OFF relay and power consumption. Subplot (b): Indoor temperature and limits. Subplot (c): Accumulated hot water in OFF mode.

Subplot (a) shows the ON/OFF state $u_i(k)$ of the device compared to the measured consumption of the device $p_i(k)$. This figure shows what was previously described, namely that the OFF state forces a heat pump to shut down, while the ON state merely allows a heat pump to run. Also, the very stochastic nature of the consumption is evident.

Subplot (b) shows the measured indoor temperature $T_i(k)$ compared to the limits $T_{\min,i}, T_{\max,i}$ which are specified by the heat pump owner. The figure shows what is generally the case for all the houses, namely that the controller allows the heat pump to run such that the temperature does not go below the limit.

The upper temperature bound is violated on one occasion, possibly caused by heating via solar irradiation. However notice that violations of the upper temperature bound is not caused by the aggregator since the aggregator cannot force the pump to run – it can only allow it to operate according to the local controller through the ON-command.

Finally, subplot (c) show the accumulated water usage during periods where the heat pump is OFF. At one instance, the accumulated water usage exceeds 30 L which causes the aggregator to send the ON-command and thereby allow the heat pump to run, see subplot (a).

4.3 Comfort of consumers

The main purpose of this work is to shift consumption in time to follow a power reference without violating the comfort of the inhabitants. In the data, we can see that the temperature and hot water constraints generally are honored as desired. However, it is important to notice that these constraints merely are mathematical representations of the real constraint, which is comfort for the inhabitants.

The inhabitants knew that the demonstration was ongoing and had the opportunity to make inquiries if they felt that the heat pump did not perform as desired. However, no inquiries were made during the test, whereby we can conclude that comfort was assured.

5. CONCLUSION

In this work, we presented an architecture for aggregation and control of flexible consumers. The basis for the architecture was a feedback controller regulating the aggregated power consumption of the portfolio towards a reference. The architecture was demonstrated on a portfolio of 54 heat pumps which together were able to follow a power reference varying between 15 and 35 kW over a period of 7 days. The strategy showed satisfactory performance and caused no discomfort for the inhabitants.

We claim that this is the first demonstration of its kind but we do not claim that the setup itself is the best that can be imagined; rather, it is a simple and transparent setup that is very suitable for a first field test in this area. Obvious improvements lie in reducing the communication delays to allow a higher controller gain and the implementation of a flexibility estimation and optimization algorithm.

Although the $35 - 15$ kW $= 20$ kW of flexibility demonstrated in this work is relatively small compared to typical regulating power bids, the demonstrated control method is scalable and thus able to handle thousands of heat pumps making it possible to provide MW deliveries.

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